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The Detection of New Methanol Masers in the $5_{-1}-4_0$E Line

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Abstract. Fifty-one object in the $5_{-1}-4_0E$ methanol line at 84.5 GHz was detected during a survey of Class I maser sources. Narrow maser features were found in 17 of these. Broad quasi-thermal lines were detected towards other sources. One of the objects with narrow features, the young bipolar outflow L 1157 was also observed in the $8_0-7_1A^+$ line at 95.2 GHz; a narrow line was detected at this frequency. Analysis showed that the broad lines are usually inverted. The quasi-thermal profiles imply that the line opacities are not larger than several units. These results confirm the plausibility of models in which compact Class I masers appear in extended sources as a result of an appropriate velocity field.

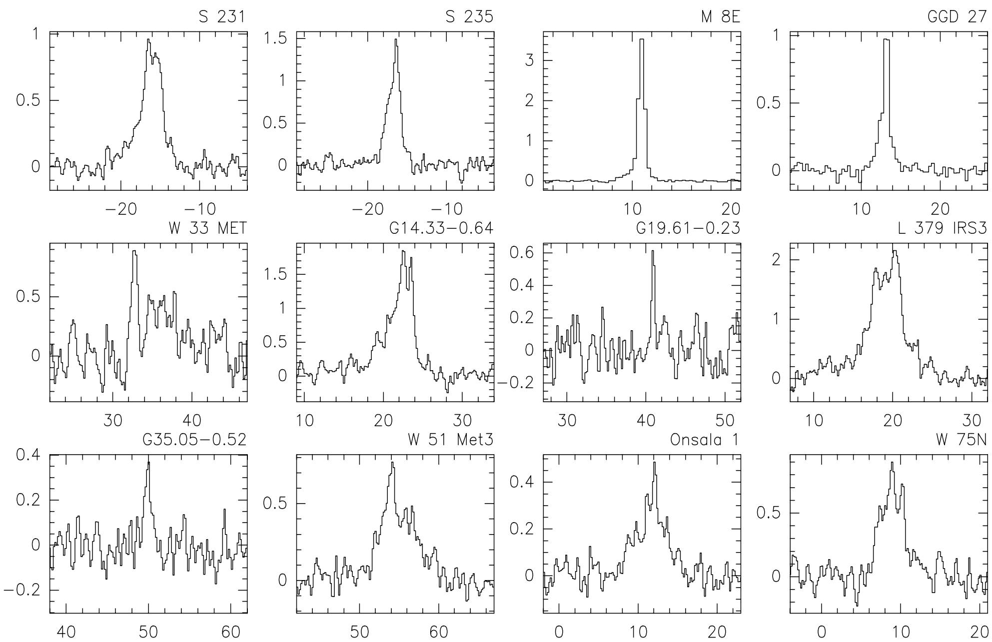
Measurements of linear polarization at 84.5 GHz in 13 sources were made. No polarization was found except a tentative detection of a weak polarization in M 8E.

1. Introduction

Methanol masers in the $5_{-1}-4_0E$ line at 84521.21 MHz were found by Batrla and Menten (1988) and Menten (1991) towards NGC 2264, OMC-2, and DR 21, but no extended survey in this line had been done. The $5_{-1}-4_0E$ transition belongs to the Class I (Menten, 1991). Its excitation is similar to that of the $4_{-1}-3_0E$ and $6_{-1}-5_0E$ transitions. Since methanol masers emit in several lines of the same class, we expect the detection of a fairly large number of maser sources at 84.5 GHz. Their parameters should be taken into account when modeling maser sources. Therefore, we made a survey of known Class I maser sources at 84.5 GHz.

2. Observations and results

The observations were carried out in May 1997 and March 2000 with the 20-m millimetre-wave telescope of the Onsala Space Observatory. A sample of 13



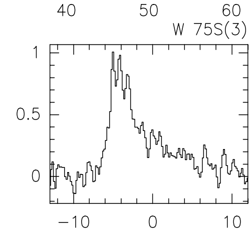


Figure 1. Spectra of 13 newly detected masers. The horizontal axis plots $V_{\rm LSR}$, in km/s, and the vertical axis plots the antenna temperature in K. 1K of antenna temperature corresponds to 31 Jy for GGD 27 and M 8E, observed at Kitt-Peak, and to 20 Jy for all other sources, observed at Onsala.

sources at 84.5 GHz was observed in June 2000 with the 12-m NRAO telescope at Kitt-Peak in remote mode from Astro Space Center.

Emission was detected in 51 of the 54 sources observed. The spectra are markedly different from those of the strongest Class I transition, $7_0 - 6_1A^+$ at 44.1 GHz. At 44.1 GHz, most of the sources from our sample have bright and narrow maser features, whereas broad quasi-thermal components dominate at 84.5 GHz, and narrow (< 1.5 km/s) features are present in the spectra of only 17 of the 51 detected sources (Fig. 1). However, it is possible that at least some of the quasi-thermal lines contain narrow maser components.

The shape of the 84.5 GHz spectra closely resembles the shape of the spectra of the same sources in the $8_0 - 7_1A^+$ (Val'tts et al. 1995) and $6_{-1} - 5_0E$ (Slysh et al. 1999) transitions at 95.2 and 132.8 GHz, respectively. The relationships between the integrated intensities of thermal lines at 84.5, 95.2 and 132.8 GHz can be fitted by the equations

$$\int T_{mb}dV(95.2) = 0.4\int T_{mb}dV(84.5) + 0.17 \tag{1}$$

and

$$\int T_{mb}dV(132.8) = 0.7\int T_{mb}dV(84.5) + 0.0 \tag{2}$$

Here T_{mb} is the main-beam brightness temperature. The relative decrease of the line intensities at 132.8, and especially at 95.2 GHz, is probably connected with the decrease of level population with increase of their energies: at a gas temperature of 35 K the population of the 8_0A^+ level is about 40% of the population of the $5_{-1}E$ level, making it possible to explain the relationships obtained.

Note the detection of narrow features at 84.5 and 95.2 GHz towards the young bipolar outflow L 1157. Unlike other methanol masers, which are associated with high-luminosity young stellar objects (above 10^3 $L_\odot$), this one is associated with an object of low luminocity (11 $L_\odot$).

3. Excitation temperature of the quasi-thermal lines

Slysh et al. (1999) showed that even quasi-thermal $6_{-1}-5_0E$ lines are typically inverted and their quasi-thermal appearance indicates that the line opacities are not large enough to cause significant narrowing. Since the excitation of the $5_{-1}-4_0E$ transition is similar to that of the $6_{-1}-5_0E$ transition it is possible that the quasi-thermal $5_{-1}-4_0E$ lines are also inverted. To test this hypothesis, we determined the excitation temperature of the $5_{-1}-4_0E$ lines using the intensities of the $4_0-4_{-1}E$ lines at 157.2 GHz, measured by Slysh et al. (1999). The excitation temperatures were derived analytically using a simple method described by Slysh et al. (1999). We applied this method to 20 quasi-thermal sources, and for each, obtained negative excitation temperature between ≈ -1.5 K and ≈ -4.5 K, i.e., the $5_{-1}-4_0E$ quasi-thermal lines proved to be strongly inverted.

The excitation temperatures derived in this way are distorted by a number of factors, such as the line opacities, influence of microwave background etc (Slysh et al., 1999). Therefore, we verified the results using a grid of LVG methanol models spanning the ranges 10^4-10^8 cm^{-3} in density, 10–100 K in temperature, and $7\times10^{-7}-2\times10^{-3}$ cm^{-3}/(km/s pc^{-1}) in methanol density divided by the velocity gradient. For each source, we selected the models corresponding to the observed ratios of the main-beam brightness temperatures of the $5_{-1}-4_0E$ line and the $4_0-4_{-1}E$ and $5_0-5_{-1}E$ lines, observed by Slysh et al. (1999). The results are as follows:

For the majority of the sources, we found that only models with inversion of the $5_{-1}-4_0E$ transition or models with unlikely high methanol abundances satisfy the observed line ratios. In G29.95-0.02, G34.26+0.15, NGC 7538, W 49N, and W 51E1/E2, the observed intensity ratios can be obtained both in models with the inversion and in realistic models with positive excitation temperatures. However, since a number of models with inversion (i.e., same as those for the other 15 sources) are applicable to these objects as well, it is not clear whether they are somehow different from the others or not.

Thus, the quasi-thermal $5_{-1}-4_0E$ methanol lines, like the $6_{-1}-5_0E$ lines, are typically inverted. This result confirms the plausibility of models in which compact Class I masers appear in extended sources as a result of an appropriate velocity field (see, e.g., Sobolev et al. (1998).

4. Search for linear polarization

In the series of observations, performed in June 2000 with the 12-m NRAO telescope at Kitt-Peak we tried to find linear polarization at 84.5 GHz towards 13 sources. We expected that Class I methanol masers may arise in a gas permeated by magnetic field and may exhibit a weak linear polarization similar to that of some H_2O masers.

Two polarization channels of the 3-mm receiver at Kitt-Peak can measure both senses of linear polarization simultaneously. Different brightness temperatures, measured in different channels would mean that the radiation is linearly polarized. One can test whether the difference is a result of linear polarization by tracing the source during a sufficiently long time range. Owing to the diurnal rotation of the sky the direction of the polarization plane will vary, resulting in regular variations of the measured brightness temperatures in the two channels and hence, in a regular variation of the difference between them.

We failed to find any difference between channels in 12 sources and obtained the upper limits for the degree of linear polarization within the range 3%–30%. The only exception is a strong maser M 8E. Here we found a small difference between polarization channels, which might appear due to a weak ($\approx$ 3%) linear polarization at 84.5 GHz. Unfortunately, this southern source ($\delta = -24^\circ$) cannot be traced along a significant part of its diurnal trajectory from the northern hemisphere. Therefore, we could not detect any regular variation of the difference between channels and cannot state that the difference is a result of linear polarization. Further polarization measurements of this source at 84.5 GHz are required.

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